

Search for inelastic dark matter with CMS

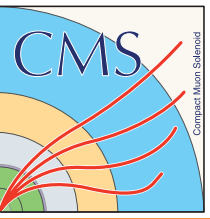
Andre Frankenthal, Princeton University

On behalf of the CMS Collaboration

UCLA Dark Matter 2023



[CMS-PAS-EXO-20-010](#)



Inelastic dark matter

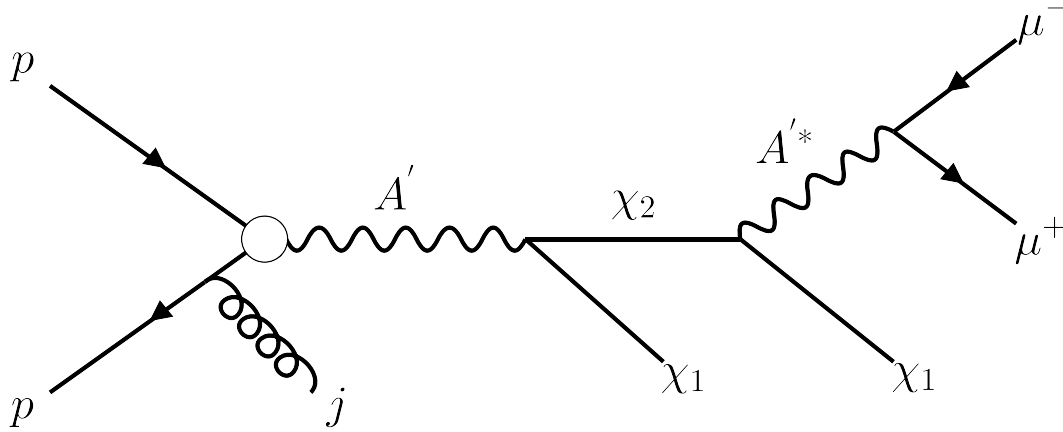
- ❖ Dark matter states χ_2 and χ_1 with near mass degeneracy
- ❖ Predominant inelastic (off-diagonal) coupling between χ_2 and χ_1
- ❖ With addition of Majorana mass term

[Smith & Weiner, PRD 64 \(2001\) 043502](#)

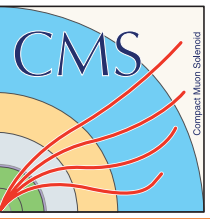
[Izaguirre, Krnjaic & Shuve, PRD 93 \(2015\) 063523](#)

$$\bar{\psi}\gamma_{\mu}\psi \simeq i(\bar{\chi}_1\bar{\sigma}_{\mu}\chi_2 - \bar{\chi}_2\bar{\sigma}_{\mu}\chi_1) + \frac{\delta}{2m}(\bar{\chi}_2\bar{\sigma}_{\mu}\chi_2 - \bar{\chi}_1\bar{\sigma}_{\mu}\chi_1).$$

Vector current couples χ_2 to χ_1 since $\delta/m \ll 1$ with δ the mass splitting



- ❖ Kinetic mixing ϵ between γ, Z and dark photon A'
- ❖ Compatible with observed thermal-relic DM abundance



Inelastic dark matter

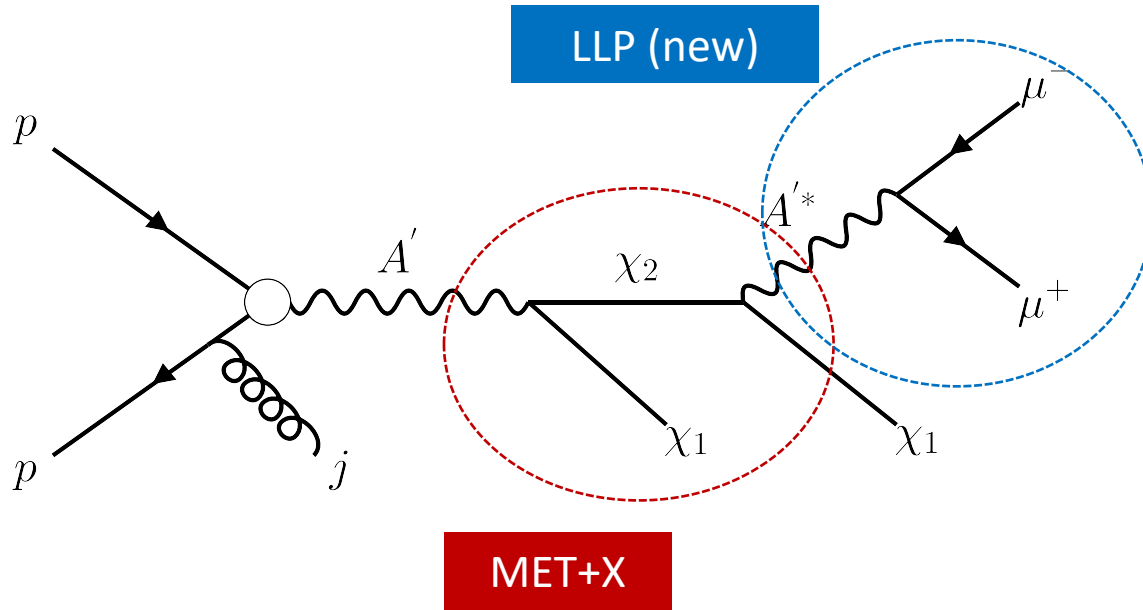
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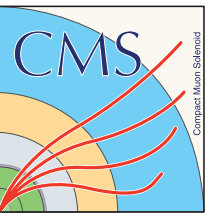
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- χ_1 mass: m_1
- Mass splitting: Δ
- χ_2 lifetime: $c\tau$
- A' mass = $m_{A'}$
- Dark sector α : α_D

- $m_1 = 1-80$ GeV
- $\Delta = \{0.1, 0.4\} m_1$
- $c\tau = 1-1000$ mm
- $m_{A'} = 3m_1$
- $\alpha_D = \{0.1, \alpha_{EM}\}$

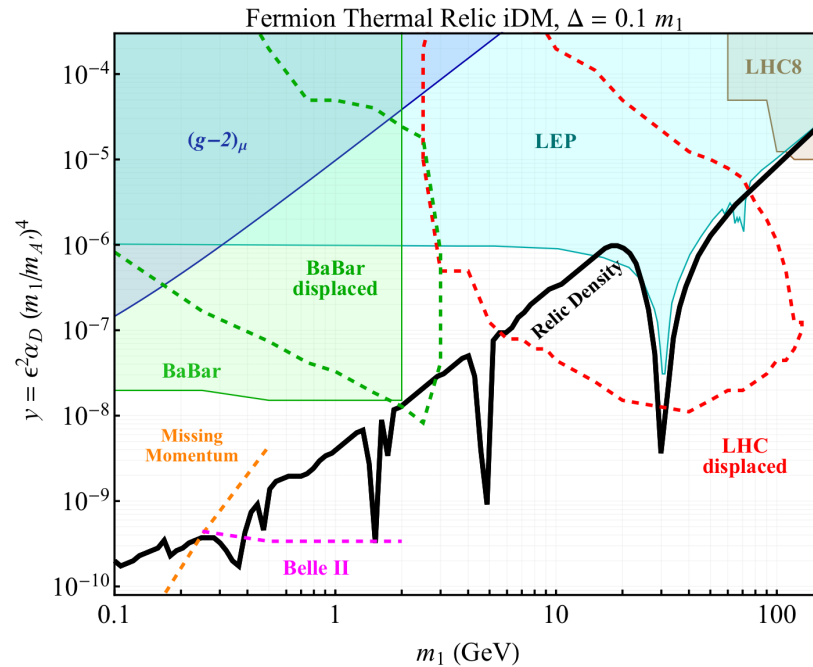


Some projections

Izaguirre, Krnjaic & Shuve, PRD 93 (2015) 063523

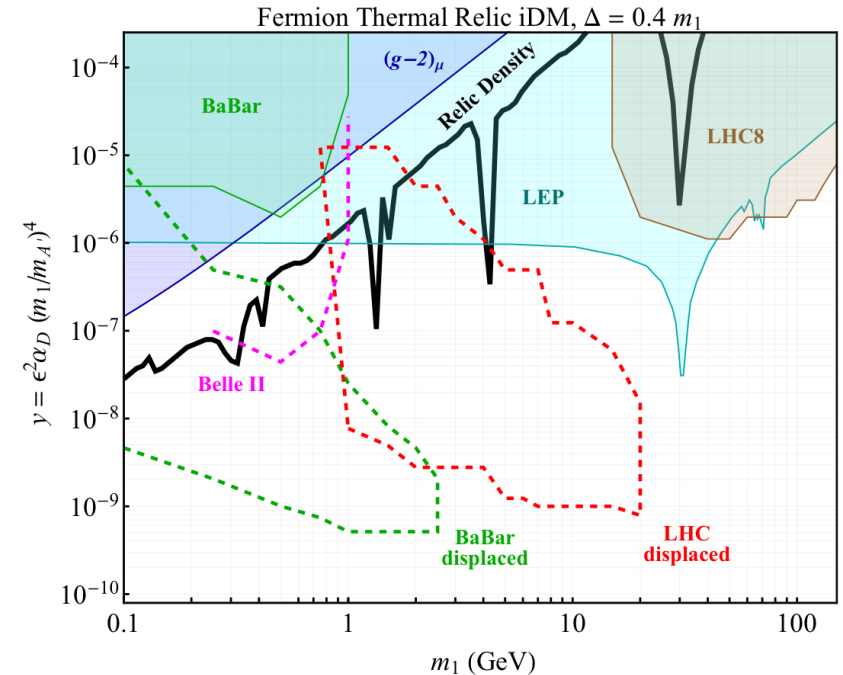
- ❖ Projected sensitivity from theory (“LHC displaced” curves)
- ❖ Lower y sensitivity for higher mass splittings, but thermal-relic DM curve also shifts up
- ❖ Lower mass sensitivity range limited by the ability to produce two muons

10% mass splitting



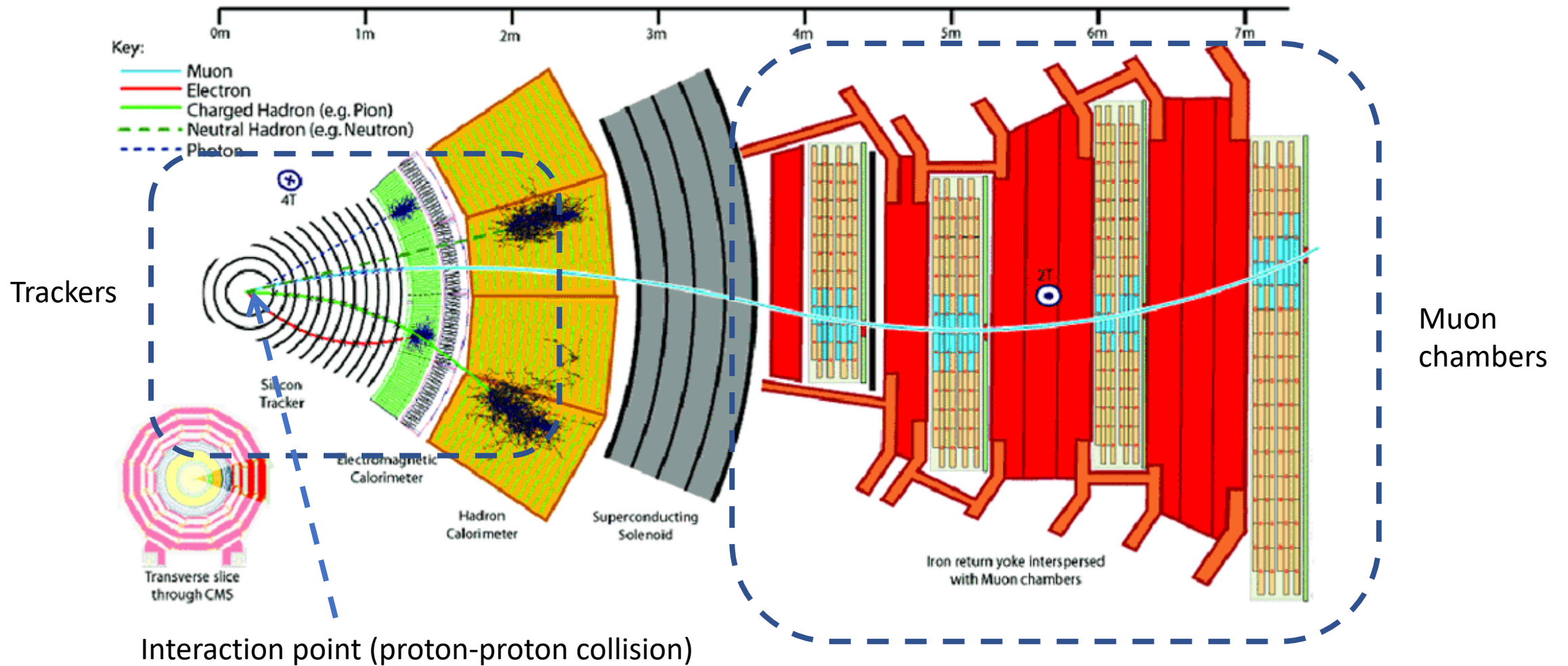
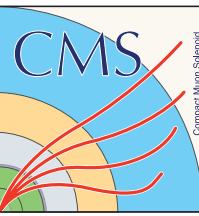
$$\sigma v \propto y \equiv \epsilon^2 \alpha_D \left(\frac{m_1}{m_{A'}} \right)^4$$

40% mass splitting



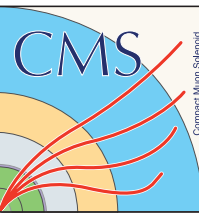


The CMS detector

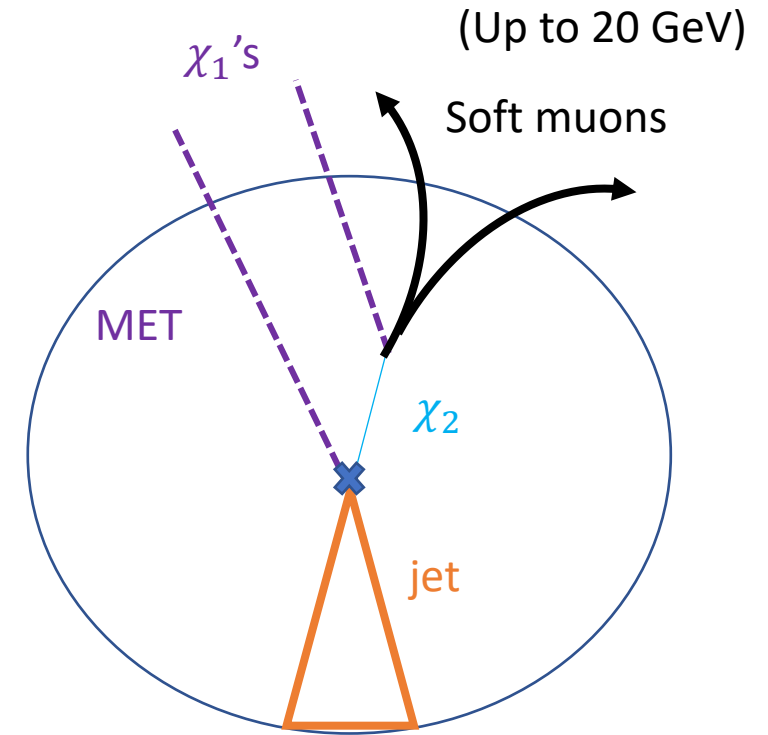
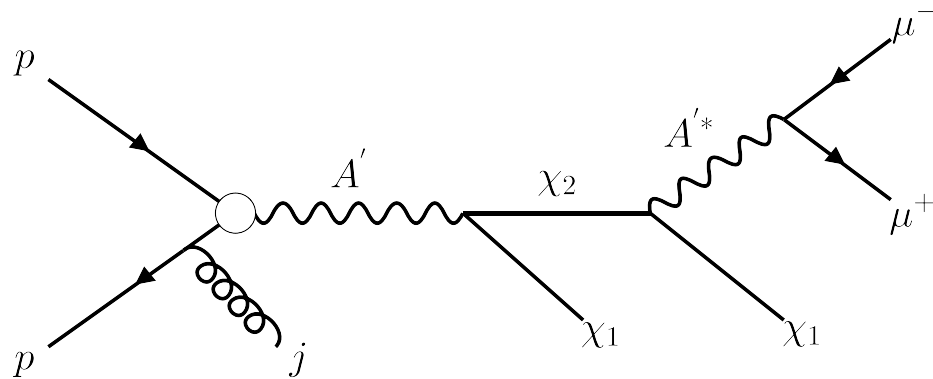




Search for inelastic dark matter at CMS



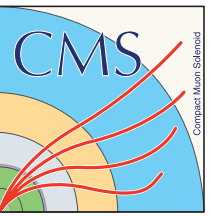
- ❖ Small mass difference (**compressed scenario**) → **soft decay products**
- ❖ Decay width of χ_2 proportional to Δ^5 and ϵ^2 → **LLP and displaced signatures**
- ❖ Production of two χ_1 's → **Significant MET activity**
- ❖ Soft decay muons → **Trigger using MET**



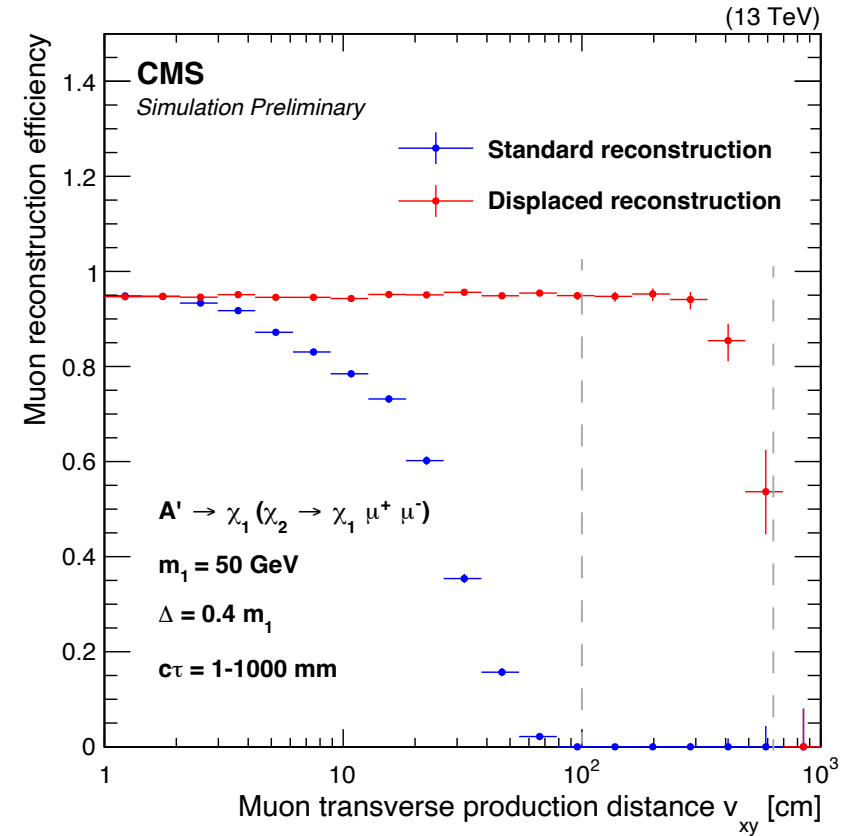
CMS transverse cross-section



Displaced muon reconstruction



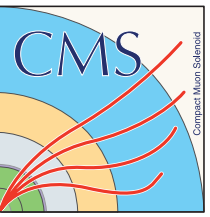
- ❖ CMS has a dedicated displaced muon reconstruction:
 - ❖ Use only muon chamber hits
 - ❖ Rely on cosmic tracking seeds
 - ❖ No beam spot constraints on the fit
- ❖ Displaced reconstruction provides high efficiency at large displacements from the interaction point
- ❖ Trade-off is worse momentum and impact parameter resolution
- ❖ → Prefer standard muon objects when they are available



Muon reconstruction efficiency



Muon object matching

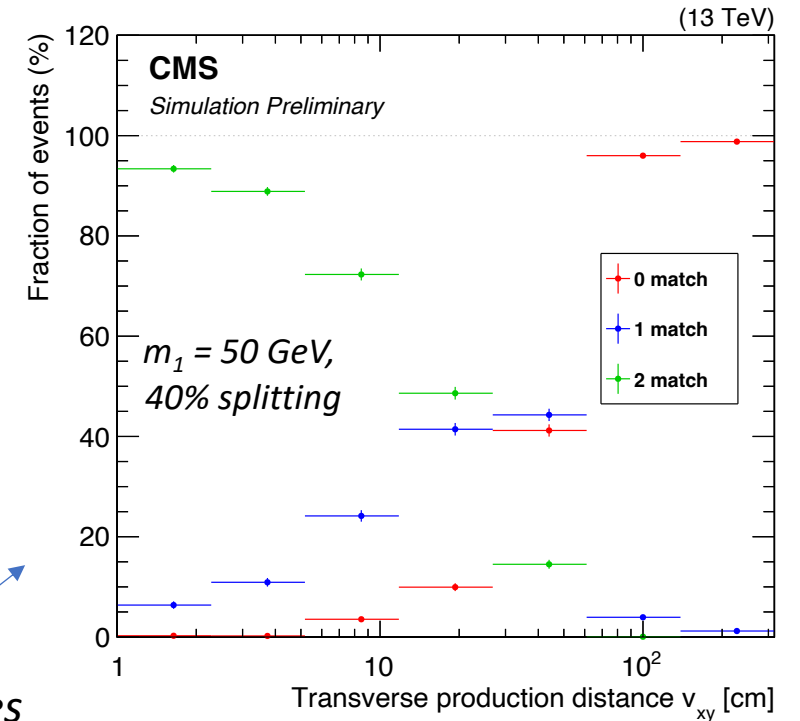
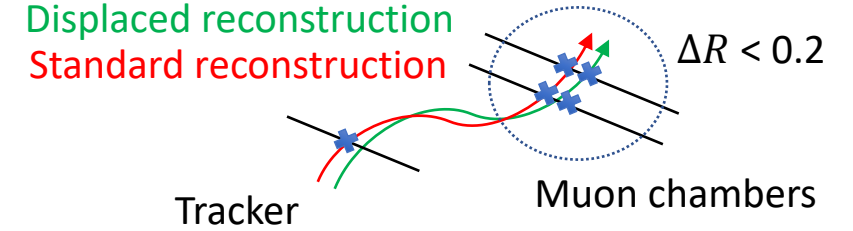


❖ Strategy:

- ❖ Require 2 displaced muon objects as baseline
- ❖ Look for geometric match between displaced and standard muons
- ❖ Split events passing baseline into 3 categories: 0, 1, or 2 muons matched

❖ Benefits:

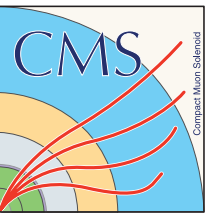
- ❖ Maximize information (resolution)
- ❖ SM backgrounds fall largely in 1- or 2-match categories
- ❖ Improve signal discrimination in 0-match



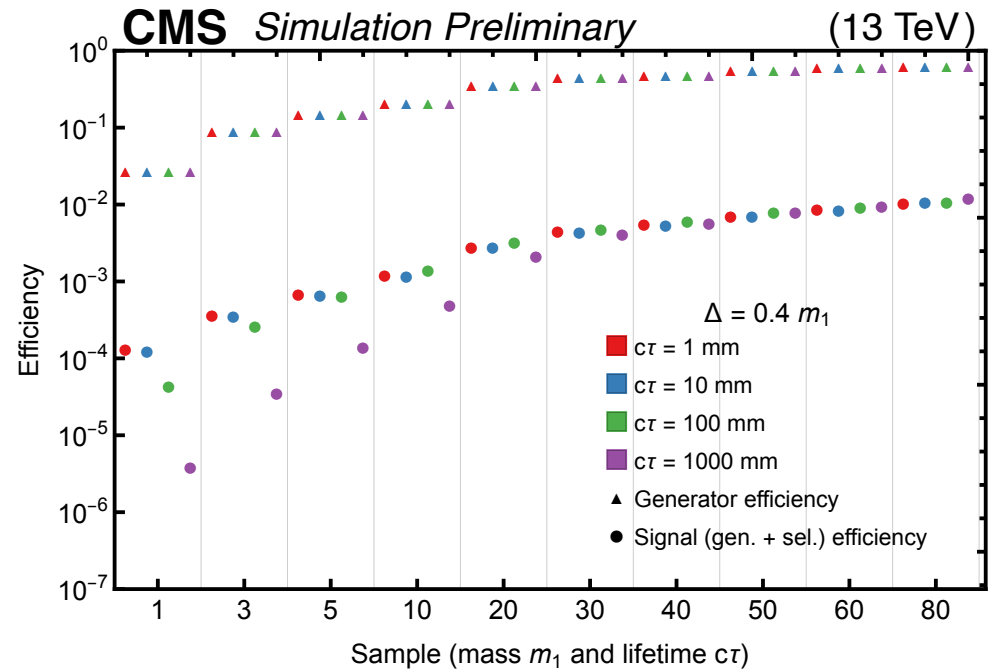
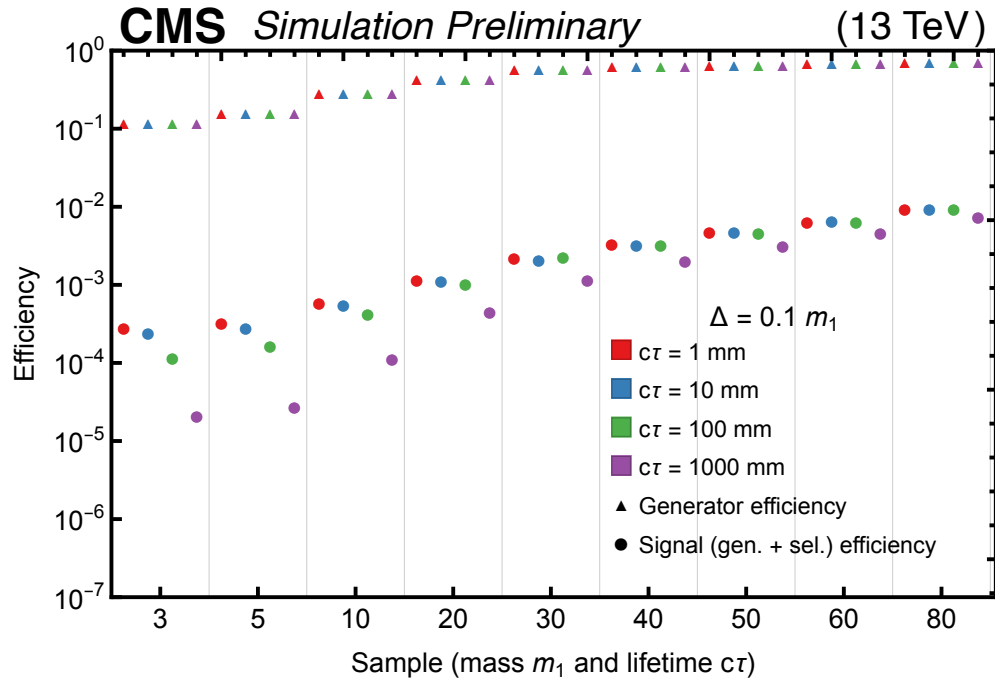
Fraction of baseline events with 0/1/2 matches



Event selection

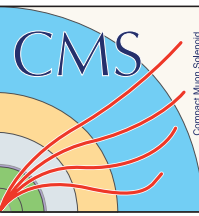


- ❖ Selection efficiency can be quite low for low-mass signal
- ❖ Compensated for by large production cross sections
- ❖ Aided by displaced muon reconstruction

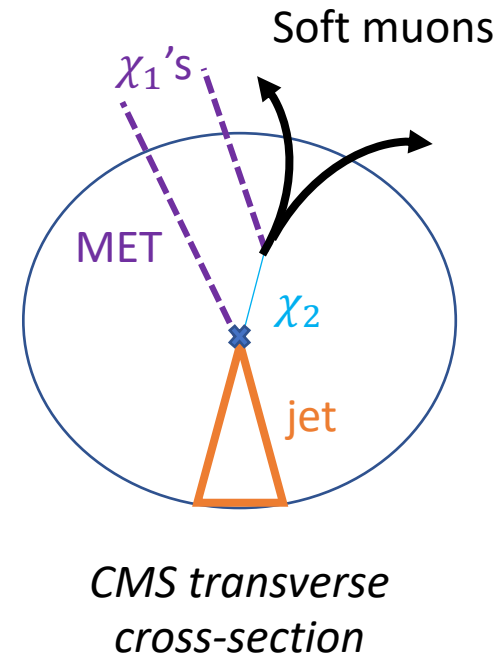
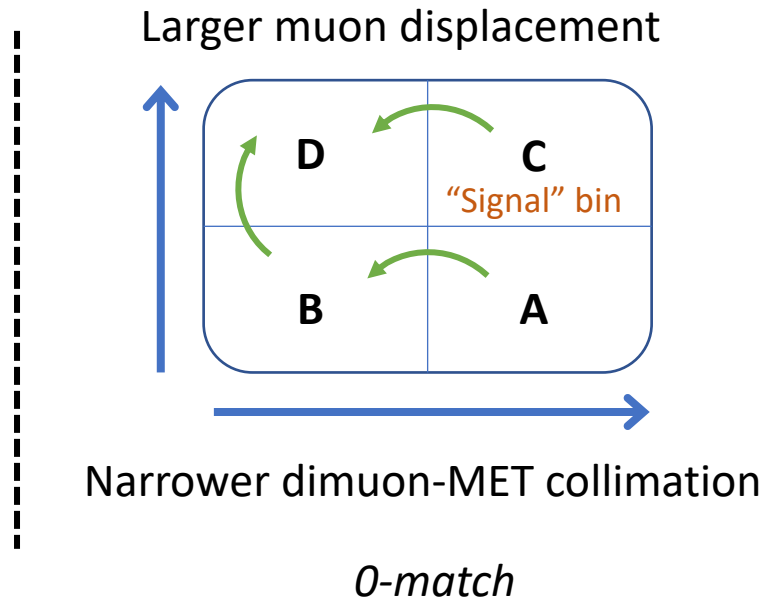
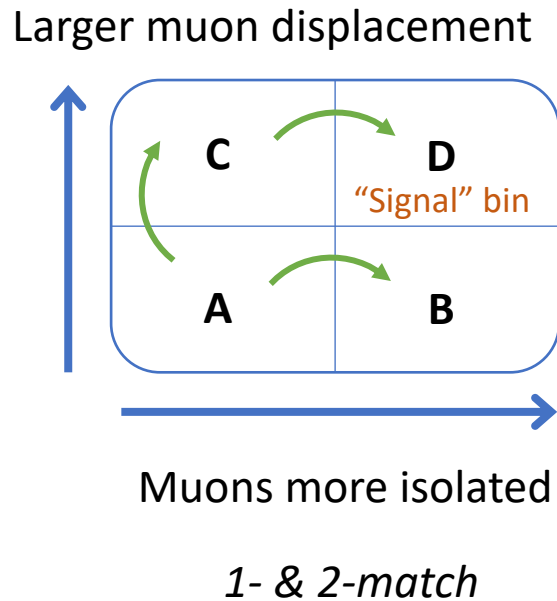




Signal extraction and background prediction

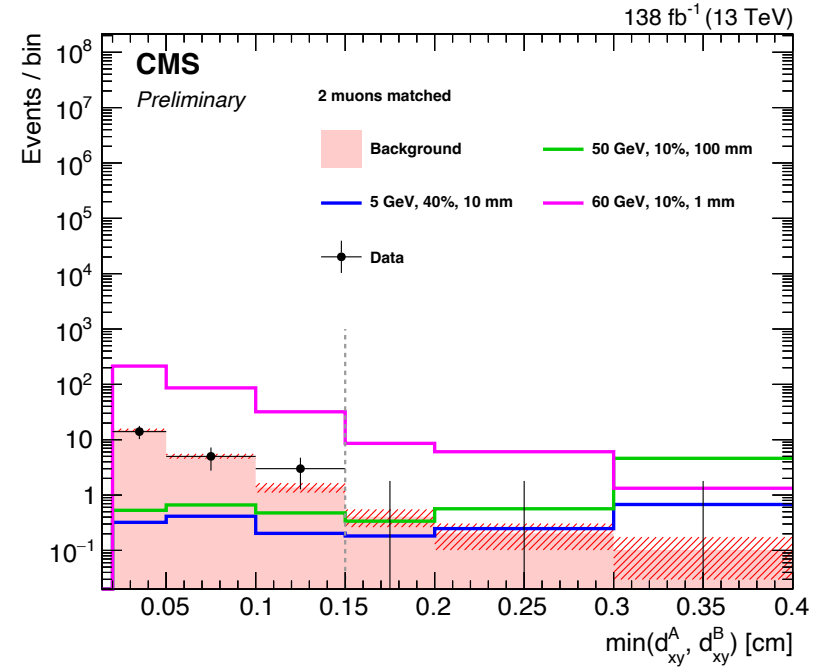
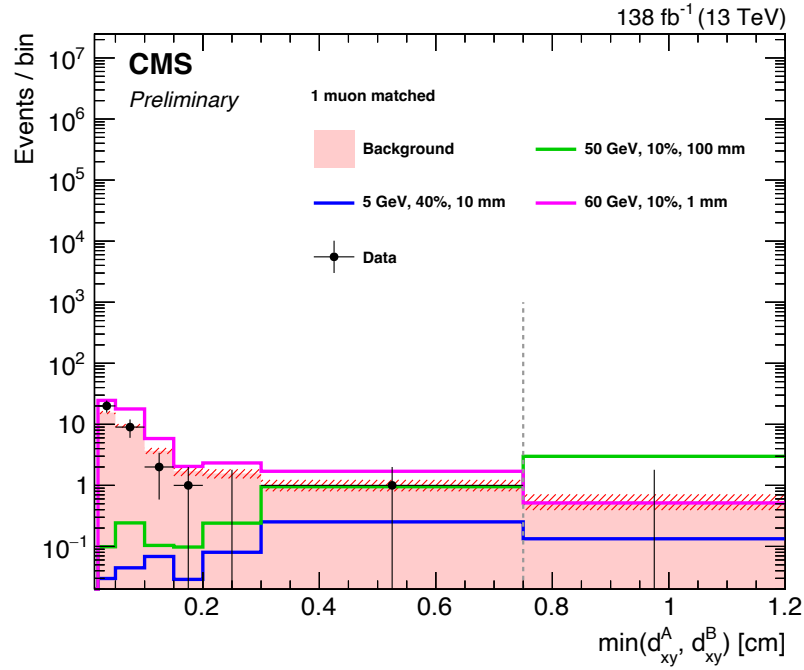
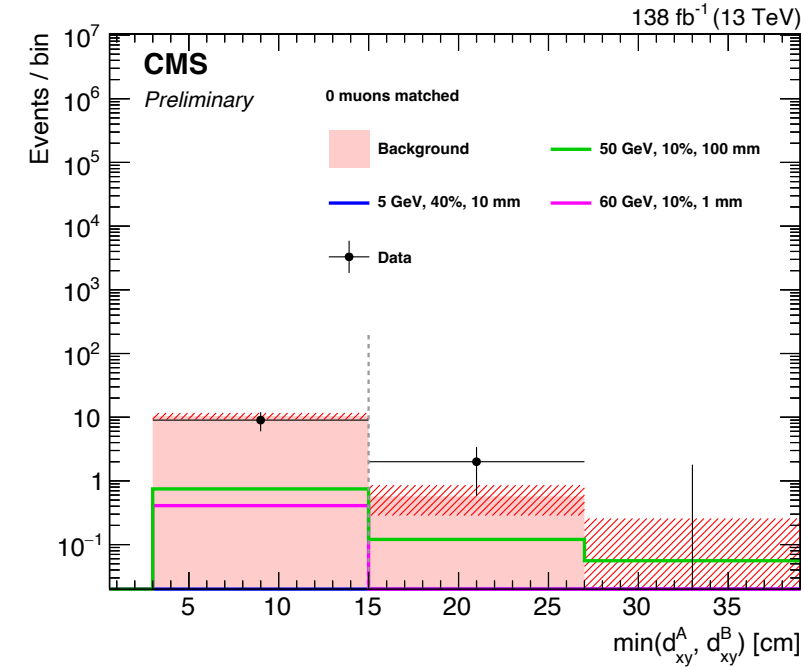
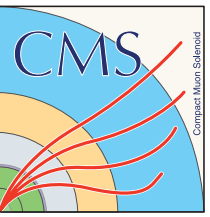


- ❖ Backgrounds have poor(er) MC modeling, so predict yields from data itself
- ❖ Modified “ABCD” procedure to simultaneously fit signal and background yields
- ❖ Fit all three match categories together





Results

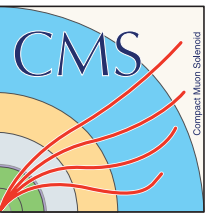


- ❖ No observed excess over predicted background
- ❖ Can place upper limits on production cross section

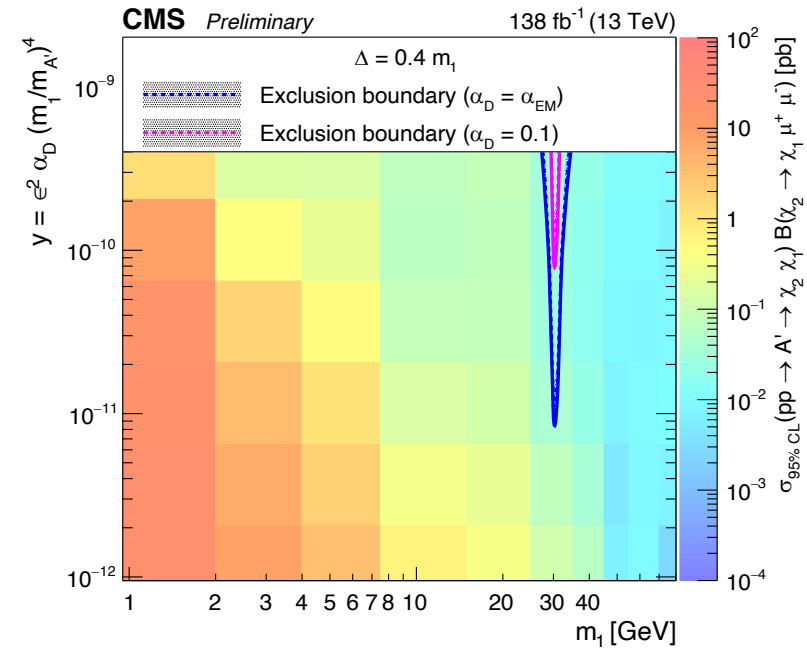
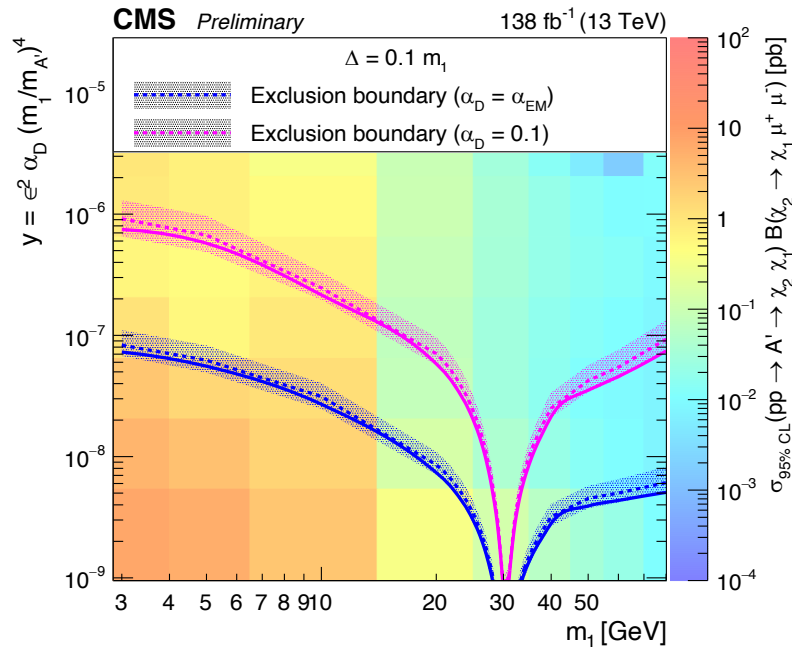
	0-match	1-match	2-match
Predicted	1.2 ± 0.6	0.5 ± 0.3	0.5 ± 0.3
Observed	2	0	0



Observed upper limits

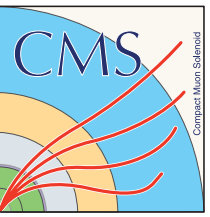


- ❖ Upper limits on $\sigma(pp \rightarrow \chi_1 \chi_2 \rightarrow \chi_1 \chi_1 \mu^+ \mu^-)$ for 10% and 40% mass splitting scenarios
- ❖ X axis denotes mass of light DM, y axis denotes $y \equiv \epsilon^2 \alpha_D (m_1/m_{A'})^4$
- ❖ Resonance enhancement around $m_1 = 30$ GeV ($m_{A'} = 90$ GeV)
- ❖ First iDM parameter space exclusion at the LHC!

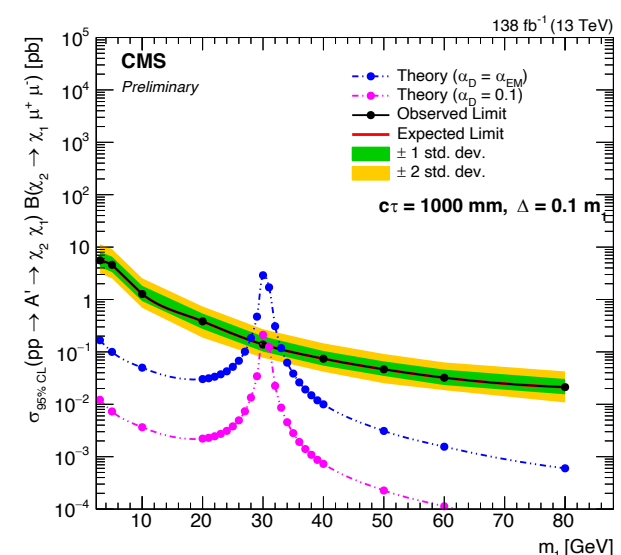
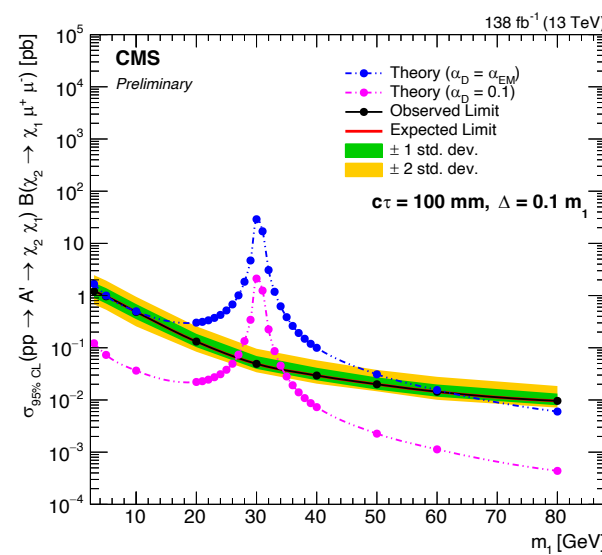
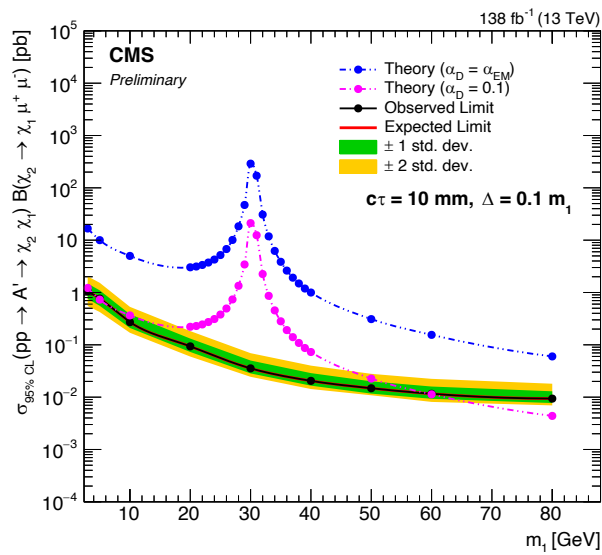
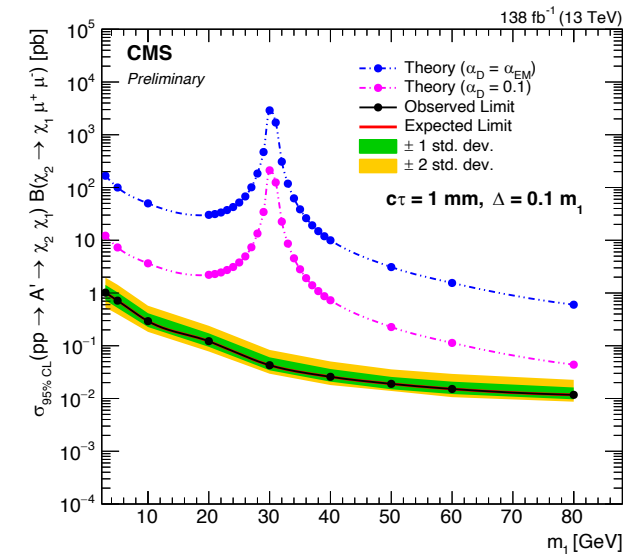




Limits vs. m_1

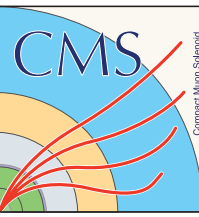


- ❖ Limits vs. m_1 for various lifetimes
- ❖ Cross section enhancement clearly visible at $m_1 = 30$ GeV
- ❖ High sensitivity to the 10% mass splitting scenario (40% splitting in backup)
- ❖ Higher experimental sensitivity to larger masses (more energetic muons)

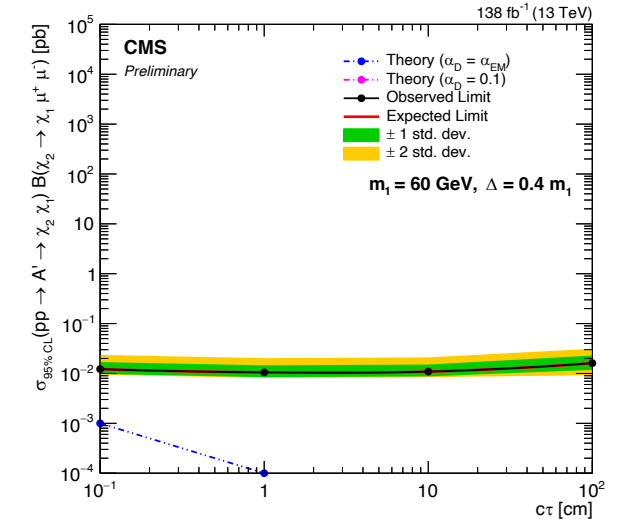
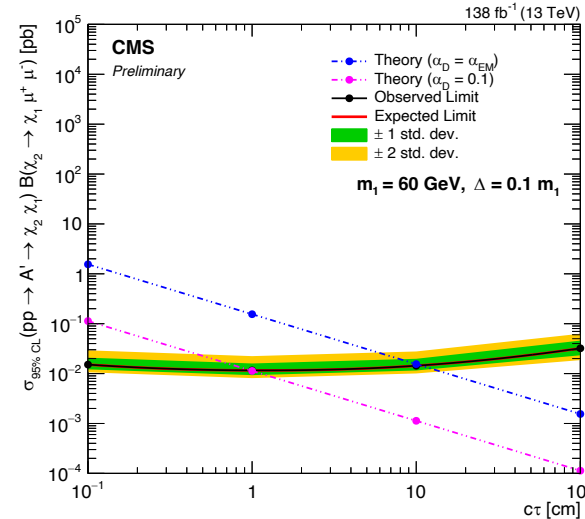
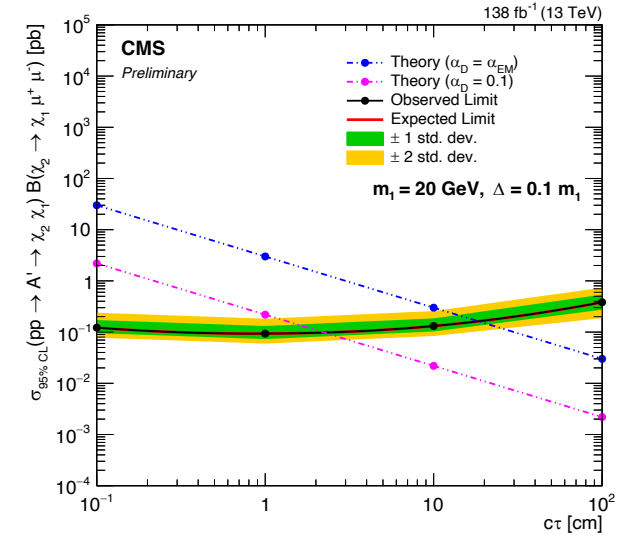
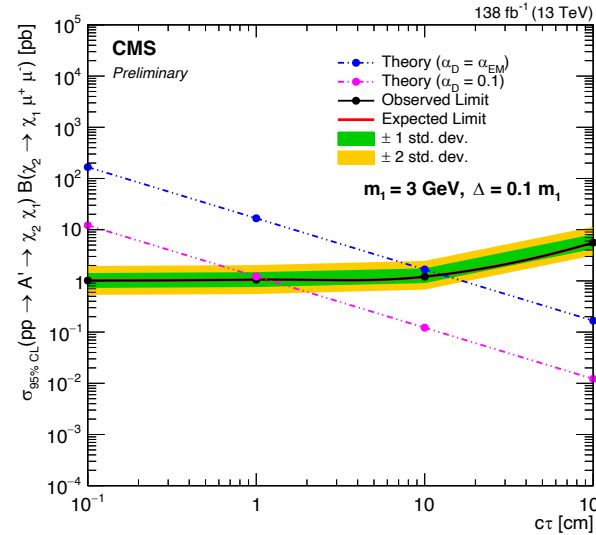




Limits vs. $c\tau$

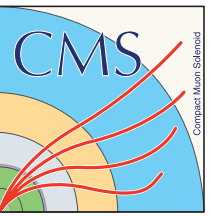


- ❖ Selection of 1D limits vs. proper lifetime for different masses
- ❖ Typical U-shaped curve with higher sensitivity to moderate lifetimes
 - ❖ Signal efficiency drops at high displacement
 - ❖ Backgrounds are more challenging at low displacement
- ❖ Production cross section inversely proportional to lifetime, mass splitting, and mass (apart from the Z resonant enhancement)





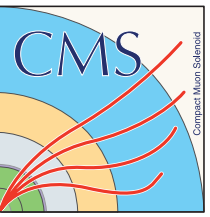
Conclusions



- ❖ Presented first dedicated collider search for inelastic dark matter
- ❖ iDM model motivated by thermal-relic DM abundance curves
- ❖ Higher experimental sensitivity to lower mass splitting scenarios
- ❖ Signal efficiency enhanced with dedicated displaced muon reconstruction
 - ❖ Still quite low efficiencies for some signal hypotheses ($10^{-4} - 10^{-2}$)
 - ❖ Aided by large predicted iDM production cross sections
- ❖ Exclusion limits placed for 10% and 40% mass splitting scenarios
- ❖ Ongoing work:
 - ❖ Include electron channel with dedicated low- p_T electron reconstruction
 - ❖ Study dedicated triggers for displaced compressed scenarios



Signal kinematics



- Distinctive features:

- Muons:

- Displaced
- Soft
- Collimated

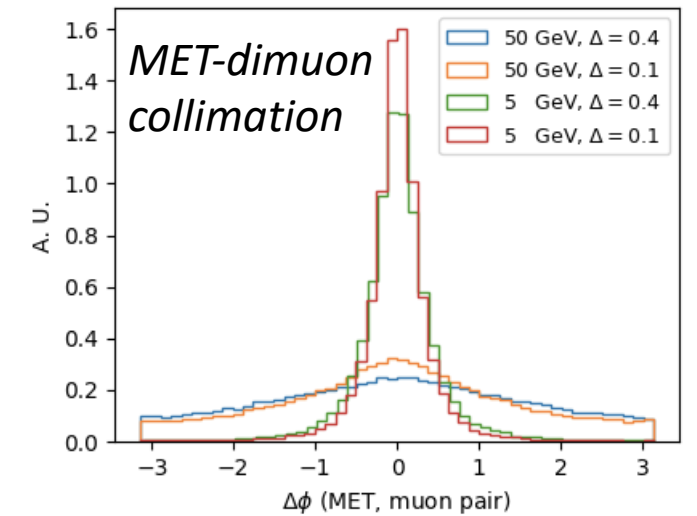
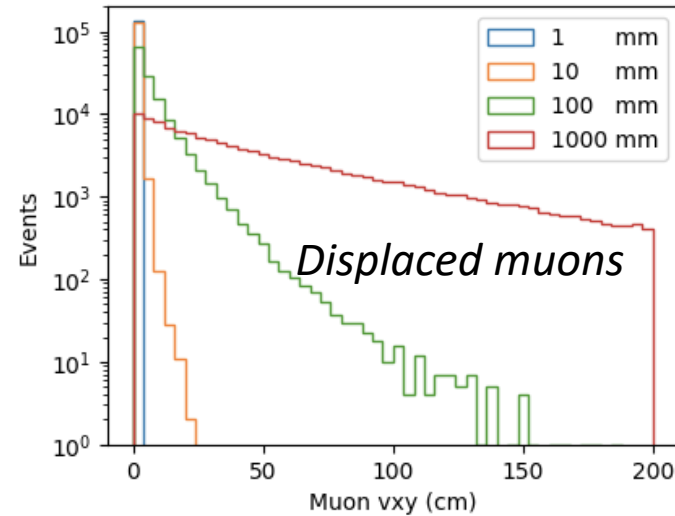
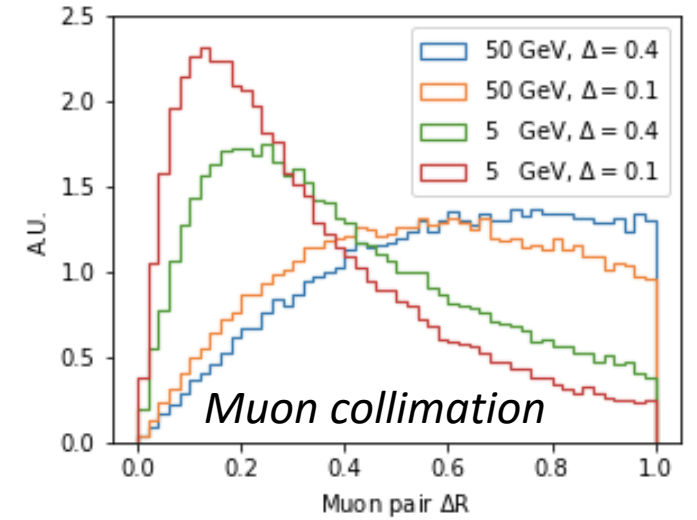
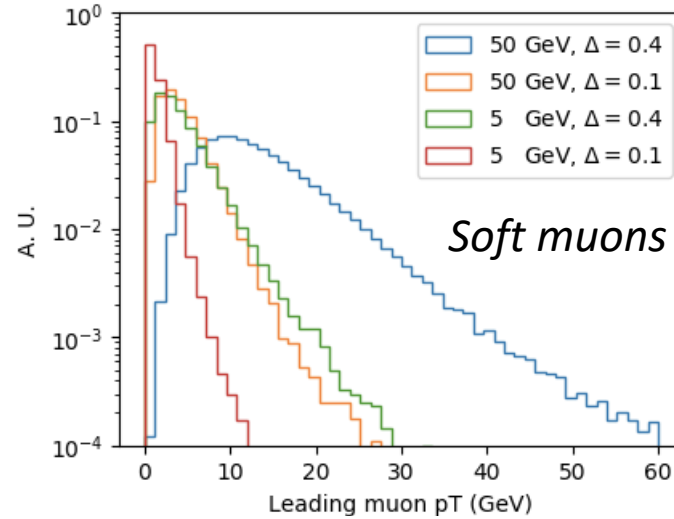
- MET:

- Significant
- Collimated with muons

- ISR jet:

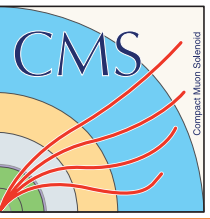
- Energetic
- Opposite MET-dimuon system

Generator MC plots
(MG5 2.6.0 LO + Pythia 8)





Full event selection



- Event selection optimized with N-1 cuts using signal significance as metric (some examples in backup)

• Jet & MET selection:

- Trigger on MET triggers
- Offline MET > 200 GeV
- 1 or 2 jets only
- Leading jet $p_T > 80$ GeV, $|\eta| < 2.4$
- Sub-leading jet $p_T > 30$ GeV
- $|\Delta\phi|(\text{MET, leading jet}) > 1.5$
- $|\Delta\phi|(\text{MET, sub-leading jet}) > 0.75$
- No b-tagged jets

• Dimuon selection:

- 2 ID'd dSA muons
- $q_1 \neq q_2$
- Vertex $\chi^2/\text{dof} < 4$ (pick lowest)
- $dR(\text{muons}) < 0.9$
- 3D angle $\alpha > 2.8$ rad
- $|\Delta\phi|(\text{MET, muons}) < 0.5$ (next slide)

• dSA ID:

- Number of muon chambers > 1
- Number of muon hits > 12
- And > 18 if no CSC hits
- Track $\chi^2/\text{dof} < 2.5$
- $\sigma(p_T) / p_T < 1.0$
- & $p_T > 5$ GeV, $|\eta| < 2.4$

• SR categorization:

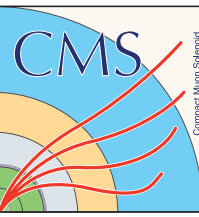
- 0, 1, or 2 dSA matches with ID'd PF muons

• "PF" Loose ID:

- Muon is a PF muon
- And muon is a Global Muon
- & $p_T > 5$ GeV, $|\eta| < 2.4$



Signal extraction and background prediction

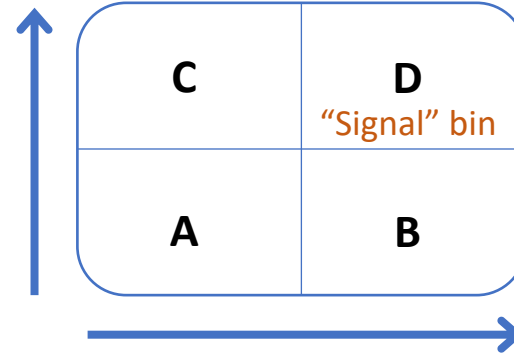


- ❖ Backgrounds have poor(er) MC modeling, so predict from data itself
- ❖ Modified “ABCD” procedure to simultaneously fit signal and background yields
 - ❖ Useful if potential signal contamination in one or more ABCD bins:

$$\begin{aligned}
 N_A^{\text{obs}} &= N_A^{\text{bkg}} + \mu \times N_A^{\text{sig}} \\
 N_B^{\text{obs}} &= N_A^{\text{bkg}} \times c_1 + \mu \times N_B^{\text{sig}} \\
 N_C^{\text{obs}} &= N_A^{\text{bkg}} \times c_2 + \mu \times N_C^{\text{sig}} \\
 N_D^{\text{obs}} &= N_A^{\text{bkg}} \times c_1 \times c_2 + \mu \times N_D^{\text{sig}}
 \end{aligned}$$

- ❖ Fit all three match categories together

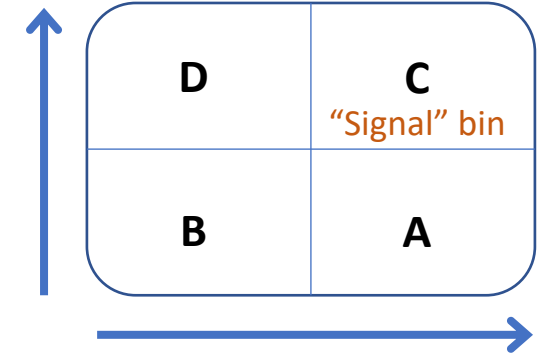
Larger muon displacement



More muon isolation

1- & 2-match

Larger muon displacement



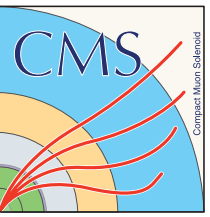
Tighter dimuon-MET collimation

0-match

- ❖ Validation of background prediction in signal-free multijet validation region
 - ❖ Require orthogonal cut: number of jets > 2
 - ❖ Good closure between prediction and observation in "signal-enriched" bin



Limits vs. m_1



- ❖ Limits vs. m_1 for various lifetimes
- ❖ Cross section enhancement clearly visible at $m_1 = 30$ GeV
- ❖ Lower sensitivity to the 40% mass splitting scenario
- ❖ Higher experimental sensitivity to larger masses (more energetic muons)

